Generating & Evaluating Feasible Alternatives Using Robust Design Simulation (RDS)

Dr. Daniel Schrage

Aerospace System Design Laboratory (ASDL)

School of Aerospace Engineering

Georgia Institute of Technology

Presentation Outline

- Introduction To Robust Design
- Taguchi's Approach to Robust Design
- Case Study for Taguchi PDOM
- A Robust Design Simulation Approach
- Case Study of RDS Application for Preliminary Design.

Robust Design Assessment and Optimization

- Robust Design is the systematic approach to finding optimum values of design factors which result in economic designs with low variability.
- Taguchi achieves this goal by first performing Parameter Design, and then, if the conditions still are not optimal, by performing tolerance design.
- Many U.S. companies have embraced the concept of addressing manufacturing variability earlier, i.e. using six sigma approaches.
- The highest payoff for Robust design Methods is to address all downstream variabilities during the System Design Phase, which necessarily involves the S&T community.

Six Sigma Quality Program

(Quality Progress, Jun 93)

- Six Sigma is defined at two levels:
  - Operational - Uses several statistical measures to characterize defect levels and process capabilities.
  - Managerial- relies on an improvement process that is used by all employees to increase the quality of products, services, and processes.
- Six Sigma relies on the Normal Distribution Theory to predict defect rates.

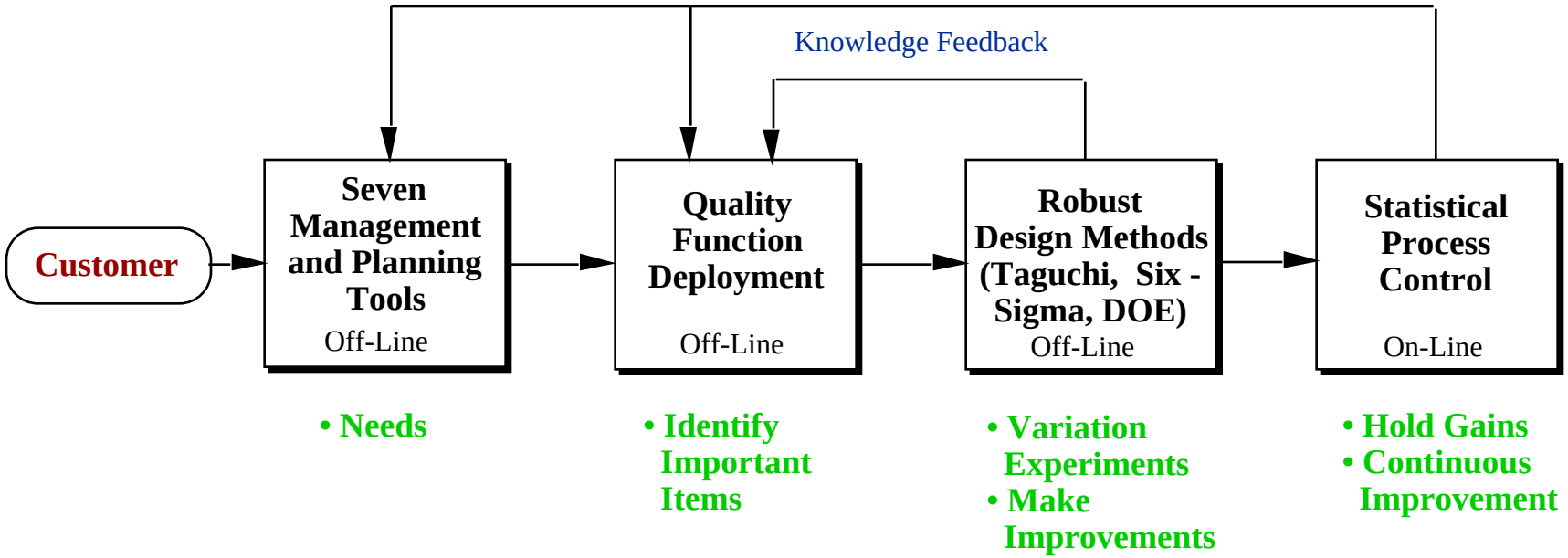
Validation of Technology/Process Initiatives

- Technology Validation
  - Validate Performance by Test or Analysis
  - Quantify Impact on Integrated Product Design
- Process / Cost Validation
  - Prototype / Demonstrate Processes
    - Representative Production Environment
    - Extrapolate and Smooth to Estimate T1
  - Supplier participation on IPTs to Define Subcontractor Demos
    - Simulation for “What-ifs”
    - Close Coordination with Cost and Price Analysis
  - Virtual Simulation to Move Down Learning Curve.

Quality Engineering:
Three Stages in Product/Process Design

- **System Design-** Earliest design phase and involves:
  - Development of a system with intended function.
  - Requires technical knowledge from science and engineering.
  - Originality / Invention / Marketing Strategy
  - Design Concept
- **Parameter Design -** involves:
  - Determination of nominal values for parameters (controllable factors) so that system is most robust.
  - Quality improvement without cost increase.
  - Signal-to-noise ratio for data analysis..
- **Tolerance Design -** involves:
  - Specification of allowable ranges for deviations in parameter design.
  - Assignment of appropriate tolerances for the nominal found in PD.
  - Cause detection that involves noise factors only.

The Quality Engineering Process



Having heard the “voice of the customer”, QFD prioritizes where improvements are needed; Taguchi provides the mechanism for identifying these improvements

Taguchi's Approach To Robust Design

Positive Points

- Objective is to minimize loss (to Society)
- Uses Signal-to-Noise Ratio to identify designs that minimize losses
- Needs small number of design simulations to obtain a result
- Employs saturated designs for control and noise variables separately

Negative Points

- Works best for on-target (tolerance) designs
- Only an intermediate step to the goal of customer satisfaction
- Computationally expensive to include non-linear effects
- Does not account for interactions between control or noise variables

Taguchi's Definition Of Quality

" Quality is minimizing the loss to society after the product is delivered"

The Taguchi Method

- A disciplined way of developing a product or investigating feasible alternatives.
- Method to design quality into the product/process design - selecting factor levels for best Quality Characteristic value.
- Ensures Robustness of design - minimizes variation about target value.
- Steps of the Taguchi Method :
  - Brainstorm Quality Characteristic and design parameters.
  - Design / conduct experiments
  - Analyze results to get optimum factor levels.
  - Run confirmation test.

Taguchi Method Features

- Design Variables
  - Control Factors
  - Noise factors
- Interactions - handled as additional factors.
- ANOVA Analysis
  - A technique which validates the statistical significance of the variation of the Signal-to-Noise ratio.

Fractional Factorial

- Requires significantly fewer tests.
- Many factors can be assessed.
- Can be used to deductively identify variables for future experimentation.
- The fraction is a carefully prescribed subset of all possible combinations.
- Taguchi provides a guideline in selecting such a standard set of orthogonal arrays.

Noise
(Causes of Variation)

- Noise: Those variables, uncontrollable or undesirable to control, which disturb the function of products or processes.
  - Examples: weather, temperature, exchange rates, pollution...
- Three types of noise:
  - Outer noise: environmental condition
  - Inner noise: tool deterioration
  - Between product noise: Piece to piece variation
- Instead of eliminating noise (expensive), design product/ processes insensitive to noise.
- A product or process that is insensitive to noise is said to be Robust.

Robustness = High Quality

Methods Of Experimentation

- Desirable Attributes:
  - Can accommodate numerous factors in relatively few tests.
  - Is balanced so that individual factor effects can be estimated.
  - Offers a high chance for reproducibility
- Historically, only one factor at a time was changed. This does not guarantee reproducibility.
- A full factorial is another approach, but is impractical because of the number of tests required.
- A partial factorial or orthogonal array allows for a mathematically independent assessment of each factor's effect, especially in evaluation of robustness over a number of experimental runs.

Taguchi Outer Array

- The optimum condition determined using the outer array approach is least sensitive to the variation from any noise factors that are included in the experiment.
- Number of repetitions is determined by the size of the outer array.
- Influence of noise factors can be assessed.
- Conditions (levels) of noise factors are obtained from the outer array.

Limitation Of Taguchi Methods

- Inner and outer array approach:
  - Very large number of experiments may be required;
    for 11 control factors and 4 noise factors 12x8 =96 runs are required
  - Not flexible to estimate the control factor and noise factor interactions.
- Loss-model approach:
  - It is less likely that expected loss can be modeled well by a low-order linear model.
  - Difficult to do the tradeoffs quantitatively when additional quality characteristics need to be considered.
  - Information obtained can not be reused.

Point Design Optimization Problems

- In general, the number of tests required to get a reasonable solution may be quite large.
- Initially, when far from optimum, sizable gains can be realized. But progress becomes considerably slowed as the optimum region is approached.
- It is possible to get held up on the surface with no apparent improvement possible, as along a rising ridge.
- The final outcome of the search procedure is a single best solution, but little knowledge is obtained about the general behavior of the system. Therefore, there is little knowledge of the sensitivity of solution near the optimum.

Robust Design

A robust design is capable of operating efficiently in a wide variety of environments, not just a single design-point situation.

- A robust design is a design with minimal variance due to external noise factors that are beyond the designer's control
- A robust design is one that is well balanced and capable of performing well in all environments.
- For one example, a robust airliner design is insensitive to changes in economic noise parameters such as the cost of fuel.

Robust Design Objectives

- Obtain objective distribution function rather that a point design solution by accounting for uncertainty or real life variability in design assumptions.
- Minimize “loss’ during off-design point operation by minimizing dependency of responses on operational parameters.
- Explore design Space
- Assess economic viability of aerospace systems.
- Assist in the decision making process.

Robust Design Methodology

- Truly multidisciplinary synthesis tool which can be tailored to specific applications.
- Environment that considers both product and process variables.
- Analysis subjected to design, manufacturing, and environmental constraints.
- Account for benefits and risks of new technologies, modeling the increase in RT&E cost realistically.

Robust Design Methodology, (Cont.)

- Transition from “point” to “probabilistic” design, accounting for risk distributions and uncertainty due to noise factors.
- Design for affordability to quantify economic viability by modeling manufacturing and airline business practices.
- Links economic viability assessment to the aircraft design via a synthesis code.
- Ability to examine the design space around the optimum to assess the robustness of the obtained solution.

Robust Design Simulation

- Uses statistical methods and tools commonly used in Robust Manufacturing Assessment (Cp, Cpk, Six Sigma...) However, RDS allows for both product and process variation and assessment.
- While Taguchi PDOM and six sigma are used in parameter design, they treat only process variability.
- System design is where RDS has it’s biggest payoff and is heavily dependent upon S&T to establish realistic and affordable technology targets, along with their variability's.

The Pareto Principle

20%	+	80%	=	100%
Vital		Trivial		
Few		Many		

Synopsis: 20% of the variables in a given system control 80% of the variability.

Strengths & Weaknesses of RSM

- Strengths
  - Allows very accurate representation of a multivariate response using a simple polynomial equation
  - Allows visual quantification of input sensitivities and trends.
  - Requires a minimal number of cases to get an accurate RSE.
  - Very Easy to implement RSE result in existing design infrastructure.
- Weaknesses
  - The RSE is valid only in the domain of the cases analyses and does not extrapolate well.
  - Works best for well balanced responses.
  - The fit of the RSE is measures only at sparse data points, not at intermediate values.
  - Very difficult to make RSEs with more that 11 independent variables.